Visual Stress Grading of Fibre-Managed Plantation Eucalypt Timber for Structural Building Applications

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Abstract

The aim of this study was to examine the impacts of visual characteristics, strength-reducing features (SRFs), and basic density on the mechanical properties of fibre-managed plantation Eucalypt timber to create effective structural grade groups. It is the intension that the results found in this study can lead to the development of a visual stress grading method for fibre-managed plantation timber in the future and influence the development of new applications for the resource in structural elements for the built environment. The plantation specie investigated in this study was *Eucalyptus Nitens*–390 sawn timber boards. The most important visual characteristics and SRFs likely to influence the mechanical properties of the boards were visually identified and measured before the boards were divided into designated groups for sampling. The impacts of the visual characteristics, SRFs, and basic density of the boards within each group on modulus of elasticity (MOE) and modulus of rupture (MOR) were determined using four-point bending test. The statistical analyses suggest three structural grade groups can categorise the resource. Strong correlations were found between MOE, MOR, and basic density with the visual characteristics and SRFs of the boards in the three grade groups.

Keywords: timber; *Eucalyptus nitens*; visual grading; basic density; bending strength; strength-reducing features.

1. Introduction

The reliability and design flexibility of timber-rich construction makes wood products an attractive option for designers and builders. It is widely recognised that timber is:

- Environmentally friendly because wood is biodegradable, recyclable, and renewable (De Araujo et al., 2016; Fidan et al., 2016).
- A sustainable building material that is widely available in nature as long as the harvested trees are replaced by new plantings (Ramage et al., 2017).
- Very low in production energy compared to other building materials such as concrete, steel, and aluminum (Santi et al., 2016).
- Structurally effective due to its high strength-to-weight capacity ratio (Chuquitaype & Elghazouli, 2016; Ramage et al., 2017).
- An effective, natural insulator because of its porous structure (Li et al., 2016).
- Light and easy to work with (Yasar et al., 2017).
- Naturally beautiful with a featured pattern that adds character and warmth.

With the increased effectiveness and sophistication of high-mass laminated timber products, demand for timber solutions in different structural applications has rapidly increased in recent decades — especially in building construction (Yasar et al., 2017). However, timber's availability for construction is also an important issue. Using fast growing plantation species like Eucalypts on short rotation harvest cycles could be a viable and necessary contemporary solution to this issue. Eucalypts are the main plantation hardwood species in the world and most are planted and managed for fibre production. While efficient for fibre production, the forestry practices used in a fibre-focused management regime generally produces small logs of low-grade wood. It is challenging to find a practical way to use fibre-managed Eucalypt in the timber and construction industry as the sawn timber and veneer recovered from this resource is young, highly variable, and has substantial strength-reducing features (SRFs) such as knots and drying defects (Nolan et al., 2005; Blackburn et al., 2010, 2011). These can limit its use in structural applications (Derikvand et al., 2017).

The Australian National Construction Code (NCC) regulates all structural applications in buildings and consequently establishes the minimum 'fit-for-purpose' requirements for structural timber. To satisfy the NCC's requirements, structural timber elements have to comply with either the requirement of the relevant structural grading standards or have independent engineering certification of their structural performance. For hardwood, the relevant structural grading standard is Australian Standard (AS) 2082 (Timber - Hardwood - Visually stress graded for structural purposes, Standards Australia 2007). Grading under AS 2082 (Standards Australia 2007) is based on the visual examination of the SRFs and other attributes of each board and allocation to it of a structural grade. Combining this structural grade with the species' typical mechanical properties assigns a stress grade to the board. In practice, this method assumes a direct correlation between the assessed visual SRFs of the board and its structural properties, and is based on correlations established on testing relationships between the visual characteristics and mechanical properties of mature wood from native forests. By contrast, fibre-managed Eucalypt plantations are quickly grown and often harvested at 15 to 20 years old. They yield logs and recovered timber that contain a high percentage of SRFs and juvenile wood. As a result, they are likely to have physical and mechanical properties that are completely different in value and in the relationship between SRFs and structural capacity from those of mature native forest wood of the same species. Given this, the methods for visual stress grading of hardwood in the current standard may not be relevant to such a resource. In this process, the origin of boards (plantation or native forests) and the specific requirements in the target application for the boards need to be taken into account. Boards may be graded and sold as individual commodity items for use in an unknown application in buildings or graded and incorporated into a purpose design component. Parts of these issues have already been addressed in previous studies (Kline et al., 2000; Piter et al., 2004; Lycken et al., 2006; Adell Almazán et al., 2008; Roblot et al., 2008; Krzosek 2011; Muñoz et al., 2011; Stapel and van de Kuilen 2014; Feio and Machado 2015; Viguier et al., 2015; Nicoletta et al., 2017). However, the relevance of visual stress grading of timber to fibre-managed plantation species is still unknown.

The goal of this study was to investigate the effects of visual characteristics and SRFs on the mechanical properties of timber boards recovered from fibre-managed plantation *Eucalyptus nitens* (*E. nitens*) and create effective structural grade groups that can be used to inform the development of a practical visual grading method for the resource. *E. nitens* was selected in this study as it is one of the most widely planted fast-growing eucalypt species in Australia. Due to its abundance, there is interest in developing new applications for the resource especially in the built environment. Specific objectives of the study:

- Investigated the nominal recovery rate and dressed-board recovery of fibre-managed plantation *E. nitens*— sawn, dried, and dressed using standard commercial procedures.
- Created a profile of material characteristics of fibre-managed plantation *E. nitens* by assessing the visual characteristics, SRFs, basic density, and moisture content (MC) of recovered boards.
- Categorised the boards into different groups based on their wood quality, SRFs, and other visual characteristics.
- Determined the modulus of elasticity (MOE) and modulus of rupture (MOR) of the boards from different quality groups to evaluate the correlations between the visual characteristics, SRFs, and basic density with the mechanical properties of the boards under uniaxial bending loads.
- Developed regression models to predict MOE and MOR values using the visual characteristics, SRFs, and basic density of the boards.
- Developed effective structural grade groups for the boards based on the results obtained.

2. Materials and Methods

2.1. Harvesting, Sawing, and Drying Processes

For this study, 29.30 m^3 of *E. nitens* logs were harvested from a 16 years old fibre-managed plantation on the northeast of Tasmania, Australia. The average small-end diameter of the logs was 345 mm. After harvested, the logs were sawn and the boards dried using standard commercial procedures. This ensured that the results would align to any future production system that used the same equipment suite and processes. Logs were sawn into boards of four nominal widths: 75 mm, 100 mm, 125 mm, and 150 mm, and a nominal 38 mm thickness. To maximise volume recovery rate, logs were plain sawn and the sapwood was retained. The lengths of the recovered boards varied. The average lengths by width were 4551 mm, 4391 mm, 4551 mm, and 4582 mm respectively. The boards were dried in pre-dryers for nine weeks under rack weights and then air-dried in the mill yard for three weeks. After reconditioning, they were dried in conventional kilns to a nominal MC of 12%. The rack weights were kept on the boards during the entire drying processes to decrease possible distortions in the boards due to rapid drying. The dry boards were finally square dressed to widths of 70 mm, 90 mm, 120 mm, and 140 mm, and a thickness of 35 mm.

2.2. Assessment of Visual Characteristics

In total, 390 boards with the four different widths were studied for a broad range of various visual characteristics and SRFs.

2.2.1. Knots and Knotholes

Knots are one of the features that can significantly affect the mechanical properties of timber and wood products (Kretschmann and Hernandez 2006; Muñoz et al., 2011; Koman et al., 2013) and the dimensions of knots in the piece are one of the key factors in the current visual stress grading standards. In this study, knots with a diameter larger than 1/4 of the width of the boards were considered major knots. This boundary diameter for major knots was chosen as timber boards that have knots with diameters equal to or smaller than 1/4 of the width of the boards can still be graded as either Structural Grade No. 1 (the best grade) or Structural Grade No. 2 in AS 2082 (Standards Australia 2007). The frequency and type of major knots were assessed in each board.

The existence of knotholes on the boards was also assessed. This criterion was mainly an indicator of the presence or absence of knotholes not their quantity or dimensions.

2.2.2. Surface checks

Surface checks with individual lengths exceeding 1/4 of the length of the boards and or surface checks with a width larger than 3 mm were examined and reported. Boards that have surface checks with a length and or a width equal to or smaller than the aforementioned values can still be graded as Structural Grade No. 1 according to AS 2082 (Standards Australia 2007)—hence, they were not considered as major surface checks in this study.

2.2.3. End splits

The length and width of end splits were measured on each board and the percentage of boards with major end splits was reported. Major end splits in this study are those that had a length larger than or equal to the width of the boards.

2.2.4. Wane

Wane is the under-bark surface of a log that appears on the edge of a sawn timber board. The amount of wane on each board was assessed and the percentage of boards with significant amount of wane was reported. Wane larger than 1/10 of the cross-sectional area, wane on the face of the boards exceeding 1/2 of the board's width, and wane on the edge of the boards exceeding 1/3 of the board's thickness were considered as significant—according to the criteria described for Structural Grade No .1 in AS 2082 (Standard Australia 2007).

2.2.5. Insect trace and fungal decay

Most standards include insect trace and fungal decay as important visual stress grading parameters for timber. Loss in the mechanical properties due to fungal decay may be severe, especially by the time that decay becomes visually apparent (Bower et al., 2003). The boards in this study were carefully inspected to detect any possible insect trace and decay.

2.2.6. Drying distortions

Distortion frequently occurs because of differential shrinkage along and across the timber during the drying process. The types of drying distortions that occur include bow, crook (spring), twist, diamonding, and cupping. Bow, crook, and twist appear along the length of the boards while diamonding and cupping can be detected across the face of the boards. In this study, bow, crook, and twist were measured for each board and the percentage of boards with impermissible bow, crook, and twist under AS 2082 (Standards Australia 2007) is reported. The boards used in this study were square-dressed, which is a conventional processing step at the mill level. This removes or significantly reduces diamonding and cupping distortions. Hence, the amount of diamonding and cupping distortions of the test boards was insignificant and therefore disregarded in this study.

2.2.7. Slope of grain

Bower et al. (2003) describes slope of grain as "the length through which a deviation in the grain occurs". Slope of grain is one of the most important factors that affects the stiffness and strength properties of timber. A board's mechanical properties can significantly decrease with an increase in the slope of grain in it (Baño et al., 2011; Viguier et al., 2015). Slope of grain can vary from one part of the board to another, especially in long and high-feature boards. In this study, the maximum slope of grain along the longitudinal axis was detected and measured for each board according to AS 1080.2 (Standards Australia 2006). Grain deviation around knots as well as localised variations in the slope of grain were disregarded—in accordance with AS 1080.2 (Standards Australia 2006).

2.2.8. Mechanical damages and unrecoverable collapse

Mechanical damage on boards usually occurs due to debarking and or sawing deviation. Unrecoverable collapse appears during the drying process. The loss of cross section area of the boards due to mechanical damages and unrecoverable collapse may influence the mechanical properties. The percentage of boards with mechanical damages and unrecoverable collapse as well as the loss of volume of the boards due to these parameters were assessed in this study.

2.2.9. Percentage of clear wood

The percentage of clear wood is an important factor that influences the mechanical properties of timber products, even though this factor is not directly considered in the current visual stress grading standards. Clear wood in this study refers to parts of each board, with at least 500 mm continuous length, that can meet the grade requirements for structural grade 'one' boards under AS 2082 (Standards Australia 2006). This allows no knots larger than 1/7 of the width of the board. In addition, surface checking longer than 1/4 of the length of the boards is not allowed. Therefore, the diameter of knots and knotholes as well as the length of surface checks on the boards were considered for calculating the percentage of clear wood. Furthermore, areas of the boards that represented any insect trace, fungal decay, wane, mechanical damages, unrecoverable collapse, and end splits were excluded from the measurement of clear wood.

2.3. Segregation of the Boards

After identifying the most important visual characteristics and SRFs of the resource, the boards were divided into five quality groups based on their visual characteristics. Group one had the least extent of apparent SRFs and group five had the most extent of apparent SRFs. The segregation was based on the percentage of clear wood in each board, the number of continuous clear wood pieces, the type of knots on the edge and face of the boards, and surface checks as shown in Table 1.

Criteria	**Group one**	**Group two**	**Group three**	**Group four**	**Group five**
Percentage of clear wood	≥ 80% in total and in not more than three continuous clear pieces or ≥ 60% in only one continuous clear piece.	≥ 60% to < 80% in total or ≥ 40% to < 60% in only one continuous clear piece.	≥ 40% to < 60% in total or ≥ 35% to < 40% in only one continuous clear piece.	≥ 20% to < 40% in total.	≥ 0% to < 20% in total.
Type of knots on the edge and face of the board	Round and oval knots	Any	Any	Any	Any
Surface checking	Not allowed	Allowed	Allowed	Allowed	Allowed
Insect trace/fungal decay	Not allowed	Not allowed	Not allowed	Not allowed	Not allowed

Table 1. Criteria used for the segregation of the boards.

Parameters such as mechanical damages, unrecoverable collapse, knothole, wane, number of knots, insect trace, fungal decay, and end split were taken into account by the measurement of the percentage of clear wood in each board, and had an indirect effect on the segregation of the boards.

2.4. Physical and Mechanical Tests

2.4.1. Static Four-point Bending test

The relationship between the visual characteristics and the actual mechanical properties of the boards was tested in four-point bending in accordance with the test procedure described in AS 4063.1 (Standards Australia 2010). Three boards were selected from each of the five quality groups for each board width using a simple random sampling (SRS) method. With this method, each board in each group had an equal probability of selection. One test sample, with a length equal to 20 times the width of the board, was cut from each selected boards and subjected to a static four-point bending test. Careful attention was taken during the sampling process to avoid selecting more than one board from the same log for each treatment. The experimental design of the four-point bending test is shown in Table 2.

Species	Width (mm)	Group one [a]	Group two	Group three	Group four	Group five	Total No. of Samples
E. nitens	70	3	3	3	3	3	15
	90	2	3	3	3	3	14
	120	1	3	3	3	3	13
	140	1	3	3	3	3	13
					Total No. of Samples		55

[a]: Less than three boards could meet the requirements of group one in boards with 90 mm, 120 mm, and 140 mm widths. Hence, no average value is reported for the mechanical properties of these treatments. The results obtained from these treatments however were included in the statistical analysis described in section 3.3.3 (where all the results were analysed as one dataset).

Table 2. Experimental design of the static four-point bending test.

In total, 55 samples with a good range of different visual characteristics and SRFs were tested. MOE and MOR values were calculated for the test samples using Equation 1 and Equation 2 (AS 4063.1, Standards Australia 2010).

Equation 1,

$$MOE = \frac{3al^2 - 4a^3}{4bd^3(\frac{\varphi_2 - \varphi_1}{F_2 - F_1})}$$

Equation 2,

$$MOR = \frac{3F_{max}\,a}{bd^2}$$

where, *b* and *d* are the thickness and the width of boards (mm); *l* is the span length (mm); *a* is equal to 1/3 of the span length or 6*d* (mm); F_2 and F_1 are respectively 40% and 10% of the maximum load (F_{max}) at failure point (N); φ_2 and φ_1 are maximum displacement (mm) at F_2 and F_1 loads, respectively.

The failure mode and the total number and type of knots in the test samples and the loading zone particularly were counted with each test (see Figure 1). It was assumed that, due to stress concentration factor, total number of knots in the loading zone can potentially have a high impact on the bending properties of the boards. Hence, in addition to the various SRFs and visual characteristics, the concentration of knots in this zone and their possible impacts on MOE and MOR values were considered.

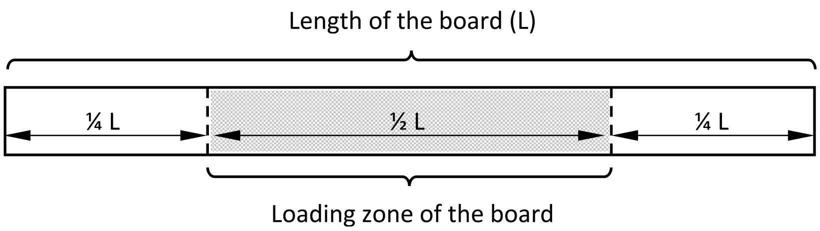

Figure 1. Loading zone in a test board.

2.4.2. Basic Density and MC

Three samples were recovered from separate areas of each tested board to determine its basic density and MC. These samples were free from defects and had a nominal cross-sectional area of 35 × 35 mm^2. In total, 165 samples were collected and assessed. The basic density was calculated using Equation 3.

Equation 3,

$$\rho = \frac{m_1}{V} \times \frac{100}{(100 + w)}$$

where, ρ is the basic density (kg/m^3); m_1 is the mass of the sample at the time of testing (kg); *V* is the volume of the samples before oven-drying (m^3); *w* is the MC of the sample at the time of testing.

The MC was calculated using Equation 4.

Equation 4,

$$w = \frac{m_1 - m_0}{m_0} \times 100$$

where, m_0 is the oven-dry mass of the sample (kg).

2.5. Data Evaluation

IBM SPSS Statistics software (version 23) was used for this study's statistical analysis. Normality of the data obtained was determined using Kolmogorov-Smirnov test. Parametric statistical analyses were performed to test for statistical significance using one-way analysis of variance (ANOVA) test. The Duncan's test was conducted to analyse the differences between the independent groups when the ANOVA showed any significant impact for the test variables. The correlations between the studied variables were analysed using linear regression analysis and the Pearson correlation coefficient.

3. Results and Discussions

3.1. Recovery Rates of the Resource

When considering a timber resource for sawlog production, the recovery rate of the useable boards from the logs plays an important role in determining the efficiency and potential profitability of using such a resource. The higher the recovery rate of the useable boards, the higher the economic value of the resource. The nominal recovery rate and the dressed-board recovery rate of the *E. nitens* resource in this study were 25.8% and 22.32%, respectively. The nominal recovery rate was calculated based on the volume of the dried boards before the final planning stage divided by the volume of the harvested logs. The dressed-board recovery rate was calculated in the same way but based on the volume of all the boards that could successfully pass the final planning process at the thickness of 35 mm, regardless of their lengths.

3.2. Visual Characteristics and SRFs

The profile of common visual characteristics and SRFs in the *E. nitens* boards, obtained from 390 samples, are given in Table 3. The average volume of clear wood in the resource was 26.3%. The average individual lengths of clear wood pieces were 1252 mm, 952 mm, 946 mm, and 805 mm in board widths of 70 mm, 90 mm, 120 mm, and 140 mm respectively. The individual length of clear wood pieces in the boards varied from a minimum of 500 mm to a maximum of about 5000 mm (Figure 2). More than 60% of the continuous clear wood pieces in the resource had a length between 500 mm to 1000 mm. Lengths of clear wood smaller than 500 mm were not measured.

Measured items	Width of boards			
	70 mm	**90 mm**	**120 mm**	**140 mm**
Average length of boards (mm)	4551	4391	4551	4582
Clear wood (%)	60.8	24.7	22.1	13.6
Average length of continuous clear wood pieces (mm)	1252	952	946	805
Boards with end split (%)	48.6	58.8	67.7	73.8
Boards with knothole (%)	60.6	89.7	77.4	77.9
Boards with major knots (%)	95.4	98.9	100	100
Boards with mechanical damage/unrecoverable collapses (%)	45.9	51.5	54.8	64.8
Boards with significant bow (%)	11	0	0	4.1
Boards with significant crook (%)	14.7	0	0	8.2
Boards with significant twist (%)	0	0	0	0
Boards with significant surface checks (%)	18.4	47.4	64.5	63.9
Boards with wane (%)	21.1	13.4	4.8	12.3
Boards with fungal decay and/or insect trace (%)	0	0	0	0
Loss of volume due to mechanical damages/unrecoverable collapses (%)	8	10.7	9.6	15.7
Multiplicity of knots	5.4	6.8	6.8	9.1
Predominant slope of grain	1:15 ≥	1:15 ≥	1:10 to 1:15	1:15 ≥

Table 3. Visual characteristics and major SRFs of the fibre-managed *E. nitens* boards.

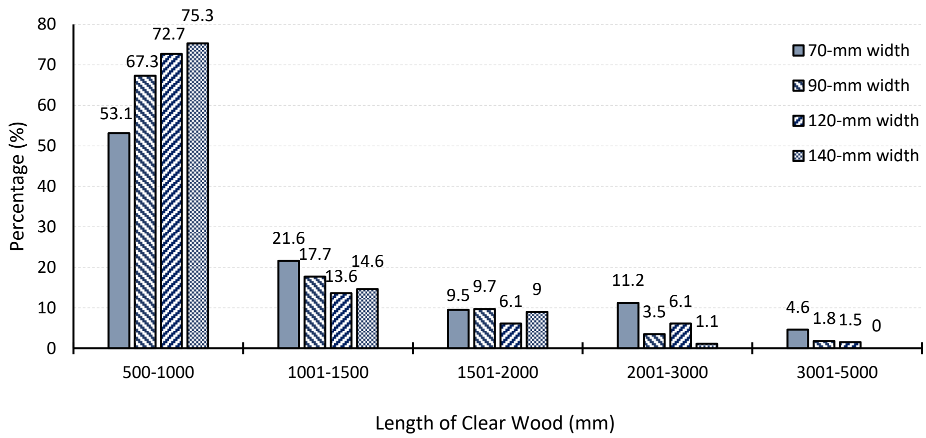

Figure 2. Distribution of the length of continuous clear wood pieces in the boards.

Knots were the most frequent SRF in the resource, followed respectively by knothole, end splits, mechanical damage/unrecoverable collapse, surface checks, wane, and distortion along the length of the boards (i.e., bow and crook). The resource was free from fungal decay and insects attack. Knots and knothole are common in the unpruned fibre managed *E. nitens* resource. While revised silvicultural techniques can reduce knot frequency, these have to be applied early in the tree's growth (Nolan et al., 2005). Consequently, knots and knothole will continue to be common SRF of timber recovered from unpruned stands currently in the ground. Another solution to knot frequency is finger jointing as major knots and knotholes can be docked out and remaining sections joined to make more structural reliable pieces. Though finger jointing is effective, this method may not be an efficient solution for this resource as the volume of clear wood was low at only 26.3 % of the recovered boards and 5.9% of the harvested logs.

The other important visual characteristic in the resource was mechanical damage that was also associated with unrecoverable collapse. These are problems arising from processing of the boards during harvesting, sawing, and drying steps. Mechanical damage was mainly from debarkers and sawing machines, while unrecoverable collapse appeared during the drying process. A significant loss in the volume of clear wood was noted in the resource due to mechanical damages and unrecoverable collapse. The loss of volume of clear wood ranged from 8% in the 70 mm boards to 15.7% in the 140 mm boards (Table 3). These negative characteristics could be reduced by utilising methods that are more appropriate for sawn timber production during harvesting, sawing, and drying processes. Inadequate sawing accuracy could intensify the development of unrecoverable collapse. The final planning process may remove unrecoverable collapse from the boards' surfaces if accurate sawing strategies are utilised (Washusen et al., 2009).

Surface checks, end splits, and distortion in the boards were substantial. These also appeared during the drying process, which suggests that the drying process for the resource needs to be reviewed and effectively modified. The amount of surface checks can significantly decrease if the logs are sawn using a quarter sawing pattern (Washusen et al., 2009). However, quarter sawing of the logs also decreases the total recovery rate of the boards (Washusen et al., 2004; 2007; 2009). The resource was free from twist distortion and the highest bow and crook rates appeared in the 70 mm boards. The 90 mm and 120 mm boards were also free from any significant distortions.

The resource proved to have a good range of slope of grain. The majority of the resource had a slope of grain of 1:15 or better. Less than 2% of the boards had the highest slope of grain of > 1:6 (Figure 3).

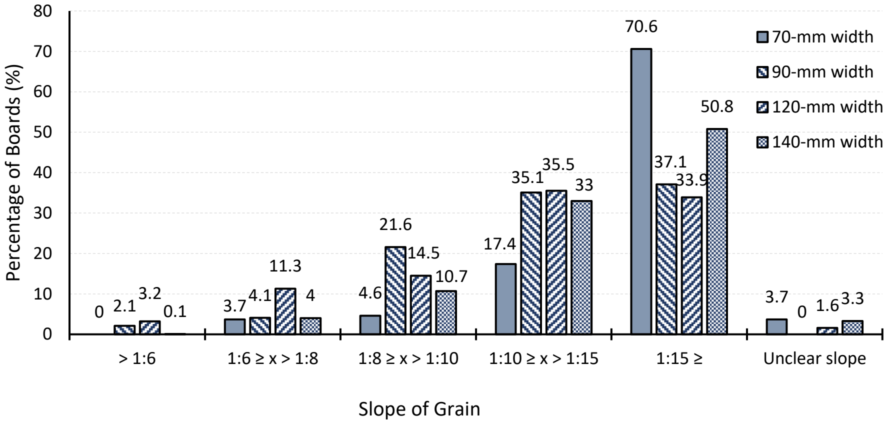

Figure 3. Variation of slope of grain in the boards.

3.3. Physical and Mechanical Properties

3.3.1. MOE, MOR, Basic Density, and MC

The overall average MOE and MOR values of the boards are given in Table 4. The average MC of the boards was 11.10 ± 0.89%. The average basic density of the resource was 480.58 ± 49.46 kg/m^3. The basic density of the fibre-managed *E. nitens* in this study was comparable to that of a plantation *E. nitens* resource studied by Blackburn et al. (2012).

In total, 27.27% of the boards tested in this study showed an MOE value between 12.0 GPa to 15.9 GPa, 41.83% of the boards had MOE values between 10.0 GPa to 11.9 GPa, and 25.45% of the boards showed MOE values between 8.0 GPa to 9.9 GPa. Only 5.45% of the boards exhibited an MOE less than 8.0 GPa. The mean MOE and MOR values of the 16-year-old unthinned and unpruned *E. nitens* were lower than that of 22-year-old thinned and pruned plantation *E. nitens* reported by Washusen et al. (2009) (Table 4). The samples tested by these researchers were obtained from the pruned parts of the logs, which is mainly consist of clear wood. However, the samples tested in the present study contained several SRFs and were not obtained from clear wood. This could be one of the reasons for the differences between the MOE and MOR values of the two resources. The other reasons could be the differences between the ages of the two resource, the sawing patterns, and the applied forestry regimes.

Species	Age	Thinned	Pruned	Sawing strategy	Nominal recovery rate (%)	MOE (GPa)	MOR (MPa)
Fibre-managed *E. nitens* [a]	16	No	No	Plain sawing	25.80	10.80 ± 1.88	43.55 ± 14.37
Plantation *E. nitens* [b]	22	6 years	6 years	Backsawn	29.8[c] to 31.2[d]	12.0[e] to 13.2[f]	99.0[g] to 108.1[h]

a: *E. nitens* tested in this study.
b: *E. nitens* tested by Washusen et al. (2009).
c, e, and g: these values are obtained from butt logs.
d, f, and h: these values are obtained from upper logs.

Table 4. Recovery rate, MOE, and MOR values of the fibre-managed E. nitens in this study against those of thinned and pruned plantation E. nitens reported by Washusen et al. (2009).

3.3.2. Modes of Failure

Predominant failure modes in the samples tested under bending loads were grain tension failure (40% of the samples) (Figure 4a), knot failure (45.45% of the samples) (Figure 4b), compression failure (9.1% of the samples) (Figure 4c), and catastrophic failure (5.45% of the samples) (Figure 4d).

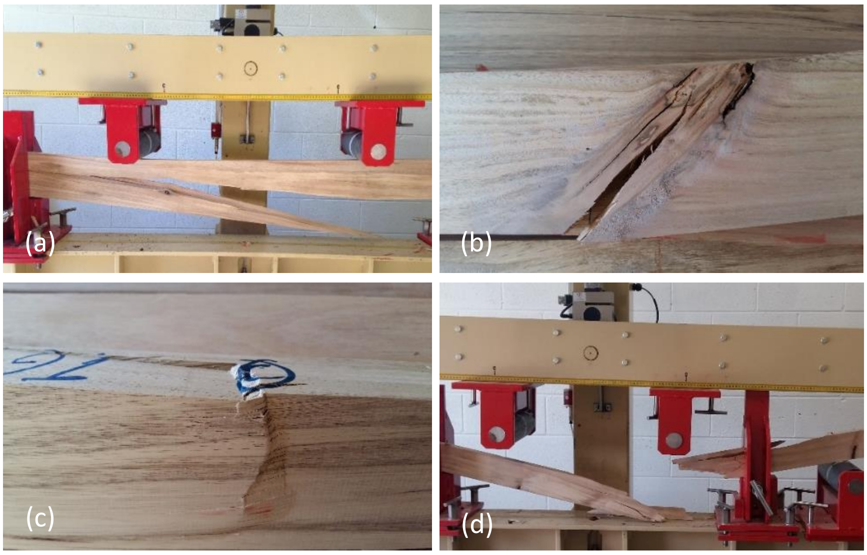

Figure 4. Failure modes of the boards under four-point bending load.

Different types of the above-mentioned failure modes were observed during the testing process. Compression failure occurred in boards that had the highest MOE and MOR values, whereas knot failure resulted in boards with the lowest MOE and MOR values. The average MOE and MOR values in the boards with compression failure mode was 13.06 GPa and 56.52 MPa respectively. In the boards with knot failure mode the average MOE and MOR values were respectively 9.98 GPa and 38.18 MPa.

3.3.3. *Impacts of Visual Characteristics, SRFs, and basic density on MOE and MOR*

In the following sections, the boards tested under bending are referred to as the tested boards and the boards from which the tested boards were extracted are referred to as the source boards. The impacts of visual characteristics and SRFs of the source boards and the tested boards on MOE and MOR values are given in Table 5. For the statistical analysis, the results of the mechanical testing of the tested boards were listed against the data obtained from the assessment of visual characteristics of the tested boards and their respective source boards to determine statistical significance—as one dataset regardless of the treatments shown in Table 2.

Independent variables	MOE	MOR
Slope of grain	***	***
Ring angle	**	NS
Ring angle × Slope of grain	***	**
Width of boards	NS	NS
Percentage of clear wood in the source boards	NS	NS
Percentage of clear wood in the tested boards	***	***
Total number of knots in the source boards	NS	NS
Total number of knots in the tested boards	NS	*
Number of knots in the loading zone of the tested boards	**	**
Type of knots in the tested boards	**	**
Basic density	***	NS

NS = not significant; * = significant at P < 0.05; ** = significant at P < 0.01; *** = highly significant at P < 0.001.

Table 5. The ANOVA results for the impacts of visual characteristics, SRFs, and basic density on MOE and MOR values.

The impact of slope of grain on the mechanical properties of the tested boards was highly significant ($p < 0.001$). The average MOE decreased by 32.02% with the increase in the slope of grain from 1:15 ≥ to 1:6 ≥ X > 1:8 (Table 6). The same increase in the slope of grain caused 53% reduction in the average MOR in the tested boards. Even though the samples tested in this study were not obtained from clear wood, the strength reduction impact of slope of grain was close to that suggested by Bower et al. (2003)—which was reported to be 60% for wood in general.

Variable	Slope of grain	N	Mean (GPa)	Duncan's groups	COV (%)	Min. (GPa)	Max. (GPa)
MOE	1:15 ≥	22	11.82	A	12.18	10.05	15.94
	1:10 ≥ X > 1:15	15	10.91	AB	10.54	9.64	12.87
	1:8 ≥ X > 1:10	12	10.19	B	21.2	7.8	15.05
	1:6 ≥ X > 1:8	6	8.03	C	10.83	6.62	8.82

Variable	Slope of grain	N	Mean (MPa)	Duncan's groups	COV (%)	Min. (MPa)	Max. (MPa)
MOR	1:15 ≥	22	51.36	A	24.07	12.7	74.3
	1:10 ≥ X > 1:15	15	45.19	AB	23.86	23.2	60
	1:8 ≥ X > 1:10	12	36.95	B	35.94	13.6	58.4
	1:6 ≥ X > 1:8	6	24.02	C	24.65	15.1	30.8

N = Number of replicates; COV = Coefficient of variance.

Table 6. The average MOE and MOR values of the boards as a function of slope of grain.

The MOE values were significantly affected by annual ring angle ($p < 0.01$) (Table 5). The highest MOE values were obtained when the angle between the loading direction and annual rings axis was 0˚ ± 15˚ (i.e., backsawn boards). The lowest MOE was obtained when the loading direction was perpendicular to the annual rings (90˚ ± 15˚ or quartersawn boards). The average MOE fell somewhere between that of backsawn boards and quartersawn boards when the angle between the loading direction and annual rings was 45˚± 15˚ (i.e., transitional-sawn boards). There was no significant difference between the MOE values of transitional-sawn and quartersawn boards (Table 7). The impact of annual ring angle on MOR values was non-significant ($p > 0.05$). Four of the quartersawn boards tested in this study had a high slope of grain of 1:6 ≥ X > 1:8—that was the worst slope of grain in the tested boards. The average MOE and MOR values in these four boards were as low as 8.19 GPa and 23.12 MPa, respectively. By contrast, only one of the backsawn boards and one of the transitional-sawn boards had the same slope of grain of 1:6 ≥ X > 1:8. Hence, the slope of grain in the four boards intensified the overall impact of annual ring angle on the mechanical properties of the tested boards. The ANOVA results also support these argument as the interaction effect of slope of grain and annual ring angle on the MOE and MOR values was highly significant ($p < 0.001$ for MOE and $p < 0.01$ for MOR) (Table 5). This could be one of the reasons for such a difference in the mechanical properties of quartersawn boards versus backsawn and transitional-sawn boards.

Variable	Annual Ring Angle	N	Mean (GPa)	Duncan's groups	COV (%)	Min. (GPa)	Max. (GPa)
MOE	0˚± 15˚	22	11.9	A	14.29	8.81	15.94
	45˚± 15˚	14	10.24	B	12.3	6.62	12.03
	90˚± 15˚	19	9.94	B	19.01	7.35	15.05
Variable	**Annual Ring Angle**	**N**	**Mean (MPa)**	**Duncan's groups**	**COV (%)**	**Min. (MPa)**	**Max. (MPa)**
MOR	0˚± 15˚	22	47.6	A	24.6	20.8	74.3
	45˚± 15˚	14	42.93	A	33.19	12.7	63.3
	90˚± 15˚	19	39.34	A	42.04	13.6	65.5

Table 7. The average MOE and MOR values of the boards as a function of annual ring angle.

There was no statistically significant difference (p > 0.05) between the mechanical properties of boards from the four different widths (Table 5).

The statistical analysis revealed that the percentage of clear wood in the source boards had no significant impact on the mechanical properties of the tested boards (p > 0.05), whereas the mechanical properties was highly affected by the percentage of clear wood in the tested boards (p < 0.001 for both MOE and MOR) as presented in Table 5. The highest MOE and MOR values were obtained with the tested boards that had a total percentage of clear wood of ≥ 80 (Table 8). The average MOE and MOR values decreased by, respectively, 21.85% and 36.76% with the decrease in the percentage of clear wood from ≥ 80 to < 40.

Variable	Clear wood (%)	N	Mean (GPa)	Duncan's groups	COV (%)	Min. (GPa)	Max. (GPa)
MOE	≥ 80	29	11.76	A	11.9	9.75	15.94
	70 ≤ X < 80	9	10.38	AB	22.25	7.35	15.05
	40 ≤ X < 70	11	9.5	B	16.84	6.62	12.57
	< 40	6	9.19	B	10.34	8.27	10.72
Variable	**Clear wood (%)**	**N**	**Mean (MPa)**	**Duncan's groups**	**COV (%)**	**Min. (MPa)**	**Max. (MPa)**
MOR	≥ 80	29	51.03	A	20.03	31.1	74.3
	70 ≤ X < 80	9	38.68	B	44.52	12.7	57.3
	40 ≤ X < 70	11	33.98	B	36.32	15.1	56.7
	< 40	6	32.27	B	37.09	13.6	45.4

Table 8. The average MOE and MOR values of the boards as a function of the percentage of clear wood in the tested boards.

Total number of knots in the source boards had no important impact on the MOR values (p > 0.05). However, the impact of total number of knots in the tested boards on the MOR values was significant at 95% level of confidence (Table 5). The average MOR decreased significantly as the total number of knots in the tested boards increased. The total number of knots in either the source boards or the tested boards did not significantly affect the MOE values (p > 0.05).

Both MOE and MOR values were meaningfully affected by the number of knots in the loading zone of the tested boards (p < 0.01) as presented in Table 5. With an increase in the number of knots in the loading zone of the tested boards from zero to four, the average MOE decreased by 23.40% (Table 9). The same increase in the number of knots in the loading zone of the tested boards reduced the average MOR values substantially by 40.72%.

Variable	No. Knots in the loading zone	N	Mean (GPa)	Duncan's groups	COV (%)	Min. (GPa)	Max. (GPa)
MOE	0 (No knots)	13	12.22	A	14.4	9.75	15.94
	1	18	10.98	AB	9.93	8.81	12.89
	2	8	10.72	AB	14.27	8.29	12.57
	3	9	9.59	B	28.68	6.62	15.05
	4	7	9.36	B	5.66	8.32	10.01
Variable	**No. Knots in the loading zone**	**N**	**Mean (MPa)**	**Duncan's groups**	**COV (%)**	**Min. (MPa)**	**Max. (MPa)**
MOR	0 (No knots)	13	57.07	A	16.47	33.8	74.3
	1	18	42.53	B	27.65	12.7	56.3
	2	8	38.43	B	42.62	15.1	63.3
	3	9	38.19	B	40.74	13.6	57.3
	4	7	33.83	B	24.06	22.5	42.1

Table 9. The average MOE and MOR values of the boards as a function of number of knots in the loading zone of the tested boards.

The type of knots in the tested boards significantly affected both MOE and MOR values ($p < 0.01$). Spike knots reduced the average MOE values by 24.47%—the average MOE was 12.64 GPa in boards with no knots. The MOE reduction impact of round knots, however, was 14.52%. Spike knots also decreased the MOR values by 41.14%—the average MOR was 60.93 MPa in boards with no knots. The MOR values decreased by 29.96% in boards with round knots.

The average MOE values of the boards were significantly affected by basic density ($p < 0.001$), whereas the effect of basic density on the average MOR values was insignificant ($p > 0.05$).

A linear regression analysis was performed to see if the MOE and MOR values of the tested boards could be predicted. The results indicated that the MOE of the tested boards might not reliably be predicted by their individual basic density—the determination coefficient was as low as R^2=0.355. The average difference between the predicted values of MOE using density and the empirical data was 11.43% (Figure 5). The results also indicated that the MOR values of the tested boards could not be predicted by their individual basic density—the average difference was 36.43% with R^2= 0.076 (Figure 6). Likewise, the MOR values could not be predicted reliably by MOE—the average difference was 24.97%, although the determination coefficient improved to R^2= 0.511. The determination coefficient for predicting the MOR values based on both MOE and basic density was R^2= 0.546. This result indicated that the MOR values for the 16-year-old *E. nitens* might not be satisfactorily predicted by

MOE and or basic density themselves. This finding is in good agreement with those reported in the previous studies on other wood species from both native and pruned plantation forests (Johansson et al., 1992; Larsson et al., 1998; Steiger and Arnold 2009; Washusen et al., 2009; Ranta-Maunus et al., 2011; Olsson et al., 2012; Lukacevic et al., 2015).

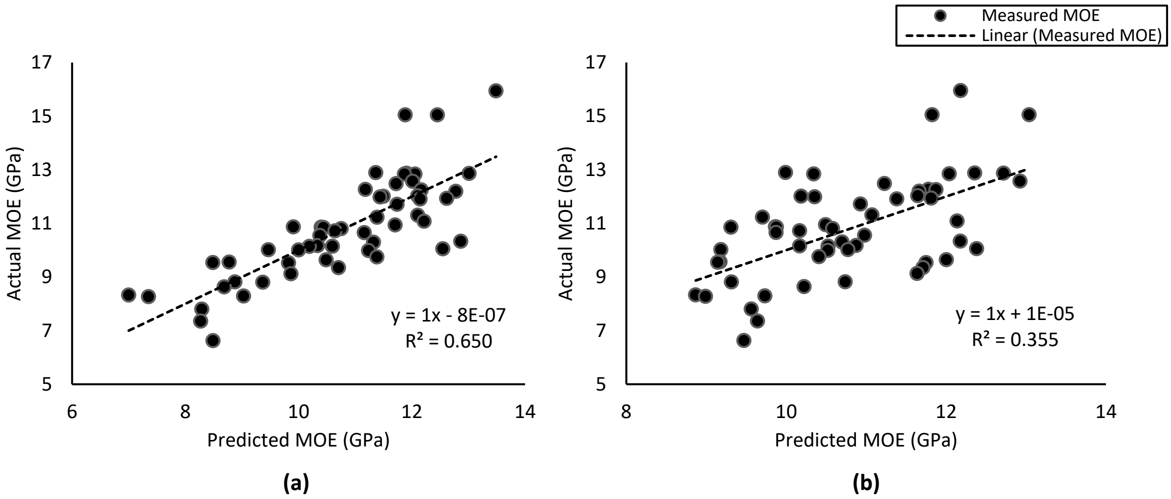

Figure 5. Correlation between actual MOE and predicted MOE values using Equation 5 (a) and basic density (b).

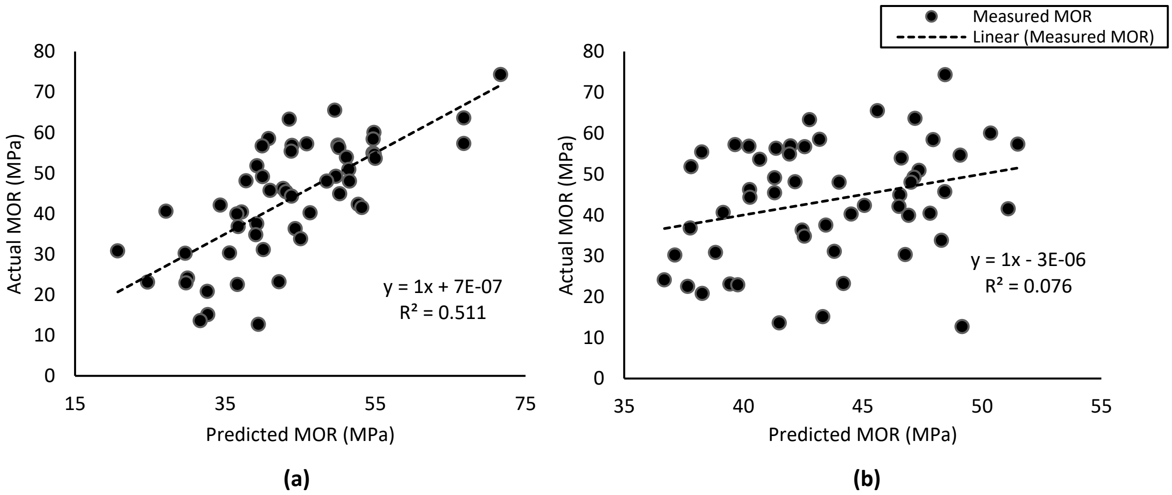

Figure 6. Correlation between actual MOR and predicted MOR values using MOE (a) and basic density (b).

The determination coefficient for the prediction of MOE considerably improved up to $R^2 = 0.650$ when the other indicating parameters including slope of grain, annual ring angle, percentage of clear wood, number of knots in the loading zone, and type of knots in the tested boards were included in the analysis. With Equation 5, the average difference between the predicted MOE values and the empirical data reduced to 7.74% ($R^2 = 0.650$).

Equation 5,

$$MOE_{(GPa)} = (D \times a1) + (R \times a2) + (S \times a3) + (C \times a4) + (N \times a5) + (T \times a6) + a7$$

where, *D* is the basic density of the sample (kg/m^3). *R* is annual ring angle: 1 for annual ring angle 0˚± 15˚; 2 for annual ring angle 45˚± 15˚; 3 for annual ring angle 90˚± 15˚. *S* is slope of grain: 1 for slope of grain 1:15 ≥; 2 for slope of grain 1:10 ≥ X > 1:15; 3 for slope of grain 1:8 ≥ X > 1:10; 4 for 1:6 ≥ X > 1:8. *C* is clear wood: 1 for clear wood < 40%; 2 for clear wood 40% ≤ X < 70%; 3 for clear wood 70% ≤ X < 80%; 4 for clear wood ≥ 80%. *N* is number of knots in the loading zone. *T* is type of knots: 0 for boards with no knots; 1 for boards with round/oval knots; 2 for boards with spike knots. a1 to a7 are regression coefficients as follow: a1 =0.016; a2 = - 0.395; a3 = - 0.490; a4 = 0.060; a5 = - 0.266; a6 = - 0.354; a7 = 5.720.

When the same procedure was followed for the MOR values of the test boards, with all the indicating parameters plus MOE included, the predicted results for a few samples could not satisfactorily be fitted to the empirical data, resulting in a high average difference of 22.55%, even though the determination coefficient improved considerably to R^2 = 0.617. In these samples, sudden failures occurred before they can reach their maximum load-carrying capacities. The possible reason for such a phenomenon could be found in the failure modes of these samples. The samples failed due to the existence of knots on the tension zone of the board (Figure 7a and Figure 7b), localised variation in the slope of grain in the tension zone (Figure 7c), and brittle failure around knots in the loading zone of the board (Figure 7d). This result suggests that the location of knots across the width of the board as well as localised variation in the slope of grain could be important in determining the maximum load-carrying capacity and MOR values of the boards. These two criteria are disregarded in most current standard methods such as AS 2082 (Standards Australia 2007). This observation is also in agreement with the findings of Lukacevic et al. (2015). These researchers indicated that the position of knots along the length and also across the width of the boards is so important that it can be used as a non-destructive indicating parameter to estimate the strength properties of the boards.

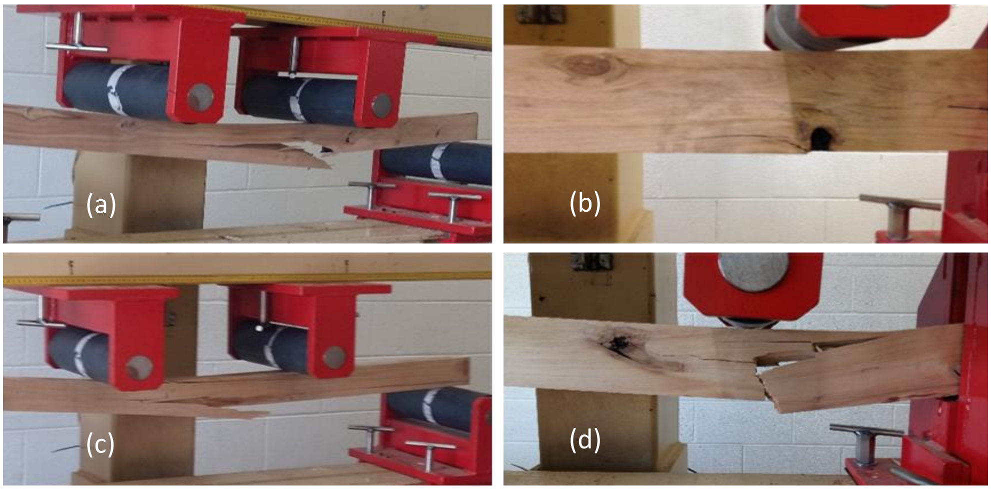

Figure 7. Sudden failure in a few samples tested under four-point bending load.

3.4. Development of grade classes

The average MOE and MOR values for the five wood quality groups are depicted in Figure 8. No significant correlation was found between the mechanical properties and basic density of the tested boards against the wood quality groups that were established based on the visual characteristics, SRFs, and percentage of clear wood in the source boards (Table 10).

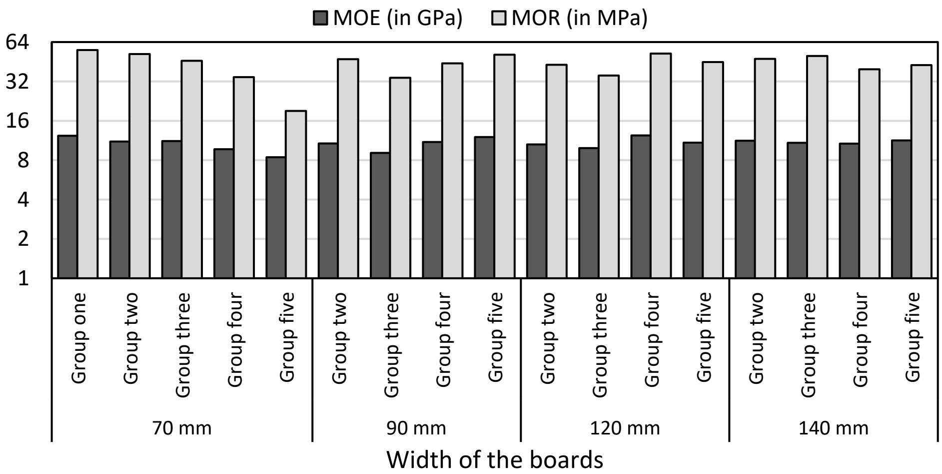

Figure 8. Average MOE and MOR values of boards in each wood quality group.

Indicating parameters	Wood quality Groups		
	Pearson Correlation	Sig. (2-tailed)	N
MOE	0.106	0.442	55
MOR	0.069	0.615	55
Basic density	0.095	0.491	55[a]

[a]: Three samples were tested for each board (i.e., 3 × 55 = 165 samples in total)

Table 10. The correlation between the wood quality groups and MOE, MOR, and basic density of the tested boards.

This result indicates that the visual characteristics of the source boards could not necessarily be representative of the mechanical properties and basic density of the tested boards. Hence, a successful grading system needs to be established based on the final dimensions of the boards, which is determined according to their target applications—this is not currently considered in the grading procedures of hardwoods at the mill level.

An attempt was made to create effective structural grade groups that can ensure reasonable correlations between the visual characteristics and SRFs with the mechanical properties and basic density of the boards. The tested boards were re-arranged in different groups but this time based on their mechanical properties, instead of their visual characteristics (repeating the process in the reverse order). The visual characteristics of the tested boards in each strength/stiffness class were analysed and the most frequent combinations of the visual characteristics and SRFs in each group were identified. The statistical analyses were then re-performed to determine the importance of correlations between the visual characteristics and SRFs with the mechanical properties of the tested boards in the new grade groups. The best correlations between the mechanical properties and the visual characteristics and SRFs were found when the tested boards were divided into the following three grade groups:

- Grade group A: MOE between 12 GPa to 15.9 GPa and corresponding MOR values.
- Grade group B: MOE between 10 GPa to 11.9 GPa and corresponding MOR values.
- Grade group C: MOE less than 10 GPa and corresponding MOR values.

The correlations between the suggested grade groups and MOE, MOR, basic density, and visual characteristics and SRFs (except type of knots) of the tested boards were highly significant at 99% level of confidence (Table 11). The density varied significantly between the three grade groups ($p < 0.001$) (Table 12). The average basic density decreased by 13.15% from grade group A to grade group C.

Indicating parameters	Grade group		
	Pearson Correlation	Sig. (2-tailed)	N
MOE	-0.877**	0	55
MOR	-0.646**	0	55
Ring angle	0.474**	0	55
Slope of grain	0.580**	0	55
Ring angle × Slope of grain	0.524**	0	55
Percentage of clear wood	-0.561**	0	55
Total number of knots	0.345**	0.01	55
Number of knots in the loading zone	0.529**	0	55
Type of knots	0.225	0.099	55
Basic density	-0.528**	0	55

** = Correlation is significant at the 0.01 level (2-tailed).

Table 11. The correlation between the three grade groups and MOE, MOR, basic density, and visual characteristics of the tested boards.

Grade level	N	Basic density (kg/m^3)	SD	Duncan's group
Grade A	15	521.27	41.68	A
Grade B	23	474.66	39.03	B
Grade C	17	452.70	47.03	B

Table 12. The average basic density values in the three grade groups.

Analysing the data obtained suggested that most of the tested boards in the three MOE classes had the combinations of visual characteristics and SRFs shown in Table 13.

Grade Level	Ring angle	Slope of grain	Clear wood	Total No. of Knots	No. of Knots in the loading zone	Probability *
Grade A	0˚	1:10 ≥	≥ 80	≤ 2	≤ 1	75.00% in group A 16.67% in group B 8.33% in group C
Grade B	45˚ and 90˚	1:10 ≥	≥ 70	≤ 3	≤ 2	81.25% in group B 12.50% in group A 6.25% in group C
Grade C	45˚ and 90˚	1:10 <	Any	≥ 1	≥ 1	100% in group C

*: This shows the possible grade level that a board may receive if they can meet the combination of features in the respective group.

Table 13. Predominant combinations of visual characteristics and SRFs in the three grade groups.

While this was not an objective of this paper, if the criteria given in Table 13 is going to be used for grading of fibre-grown *E. nitens*, the probability of existence of over-graded boards in grade group A might be 25%. Using the criteria identified for grade group B, 12.50% of the boards might be downgraded and 6.25% of the boards might be over-graded. None of the boards might be over-graded with the criteria identified for grade group C. A bigger sample size in future research may improve the accuracy of such a method. It must be noted that there could be levels of uncertainty and inconsistency associated both with this method and with visual grading of timber in the first place—

as suggested in previous studies as well (Kline et al., 2000; Roblot et al., 2008). As an instance, the results in the present study showed that the strength/stiffness of the boards are higher when the slope of grain is 1:10 or lower. However, some of the boards that were categorised in the grade group C, which was the worst grade group, had a slope of grain equal to 1:10 or even better. Another example is the annual ring angle. Based on the results, the strength/stiffness of the boards is the highest when the annual ring angle is 0˚ ± 15˚ (backsawn boards). However, the stiffness in some of the boards with the annual ring angle of 0˚ ± 15˚ was as low as 8.5 GPa (which includes in grade group C). The same issues are associated with the current standard methods on visual grading of timber. Laboratory testing on visually graded boards in previous studies revealed that a small percentage of the boards exhibited a strength class below their respective grade level, while a high percentage of the boards were meaningfully stronger than their suggested grade level in the relevant standard (Kretschmann and Hernandez 2006). While this gives a reasonable safety factor from an engineering point of view, there is a good chance that using the current visual stress grading methods significant amounts of quality boards are downgraded. On the other hand, over-graded boards, even a small percentage, can be dangerous as they might be used under load levels that they are unable to carry. Therefore, the effectiveness of the current standard methods for visual stress grading of timber needs to be addressed considering these issues in the future studies.

4. Conclusions

The following conclusions were drawn from the results obtained in the present study and the statistical analyses:

- The recovery rate of boards from the 16-year-old fibre-managed plantation *E. nitens* in this study was lower than that of a 22-year-old thinned and pruned plantation *E. nitens* reported in the literature.
- Knots and knotholes were the most important SRFs of the boards recovered from fibre-managed plantation *E. nitens*.

- Substantial mechanical damages, unrecoverable collapse, surface checks, end splits, and drying distortions were associated with the boards recovered from the resource. This may suggest that current harvesting, sawing, and drying regimes are unsuitable for this process.
- The visual characteristics and quality of long boards could not necessarily be representative of the mechanical properties when the boards are cut to a subsequent length. Hence, a two-step visual stress grading process may be more reliable—the first step at the mill and the second step when the boards are cut to the final dimensions required in their target applications.
- MOE and MOR of the fibre-managed *E. nitens* boards were significantly affected by annual ring angle, slope of grain, number of knots in the loading zone, and type of knots. The MOE of the boards was significantly affected by basic density. The impact of total number of knots on MOR values as well as the interaction impact of annual ring angle and slope of grain on both MOE and MOR values were also statistically significant.
- MOR values could not be predicted satisfactorily by either basic density or MOE of the boards. MOE values might be predicted using a multiple linear regression equation that was developed in this study based on the correlations between the visual characteristics and SRFs with mechanical properties of the boards. It might be possible to develop the same procedure for other species based on relevant laboratory testing in future studies.
- Three structural grade groups with their respective criteria were proposed for fibre-managed plantation *E. nitens* boards in this study. Strong correlations were found between the three grade groups and the visual characteristics, SRFs, basic density, and mechanical properties of the boards.

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